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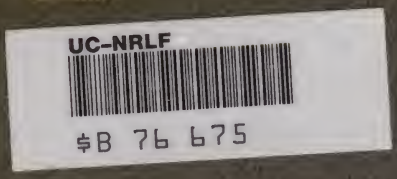

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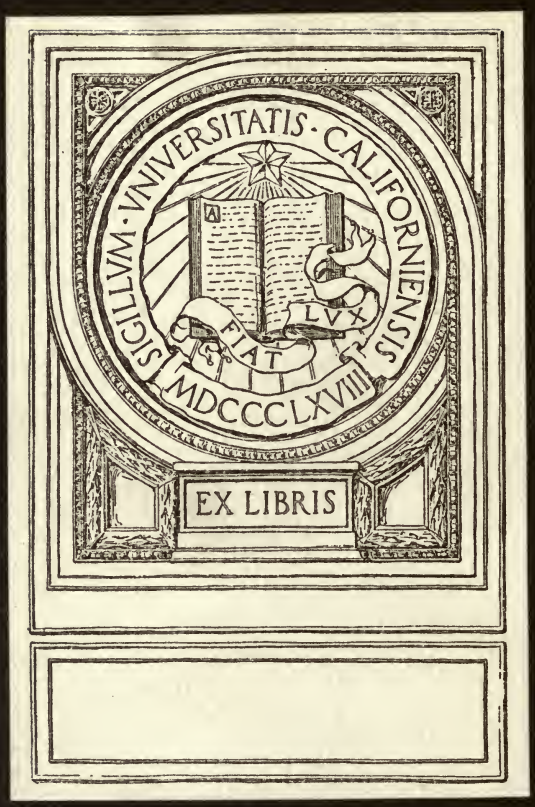
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BULLETIN No. 4.

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH.

ADVISORY COUNCIL.

MEMORANDUM

ON

SOLID LUBRICANTS.

LONDON:
Printed and Published for the Department of Scientific and Industrial Research by His Majesty's Stationery Office, and to be purchased at any of the addresses shown overleaf.
1920
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(*Continued on p.* iii *of cover.*)

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PREFATORY NOTE TO BULLETIN ON SOLID LUBRICANTS.

This bulletin has been prepared by a Committee of the Department in connexion with the survey of the field for research on lubricants and lubrication. The Department had received various requests for information in connexion with the use of solid lubricants both alone and when mixed with oils for lubricating purposes, and it appeared to the Advisory Council that, as their Committee had been dealing with this question, a memorandum embodying existing knowledge on the subject would be of service to engineers and users of machinery at the present time.

It is with this object in view that the Bulletin has been prepared, but it is necessary to point out that the present state of knowledge of the general question of lubrication is very incomplete. Little is known concerning certain theoretical matters of fundamental importance to users of lubricants. Accordingly, in issuing the pamphlet at the present time, the Advisory Council desire that it should be regarded rather as a summary of existing literature than as an authoritative statement based upon actual research work.

Certain results of experiments carried out at the National Physical Laboratory, both for the Committee and for the Air Ministry, are referred to in the present memorandum. Full particulars of these experiments are not given in this Bulletin; they will appear in the Committee's final report. The Advisory Council desire to express their indebtedness to Mr. T. C. Thomsen for the preparation of this memorandum and to Mr. L. Archbutt for his collaboration in connexion with the chemical analyses of graphites.

Department of Scientific and Industrial Research,

15, Great George Street, S.W.1.

SOLID LUBRICANTS.

Several kinds of solid materials are used for lubricating purposes, such as graphite, talc, soapstone, mica, flowers of sulphur, white lead, &c.

Some of these solid lubricants, such as flake graphite or mica, possess a tough, flaky, foliated structure which enables them to resist pressure without disintegration. Others, such as amorphous graphite or flowers of sulphur, are easily crushed into a fine powder when exposed to pressure.

Again, solid lubricants may be so finely divided as to enable them to be suspended in colloidal form in a liquid carrier. The colloidal graphite preparations, Aquadag and Oildag, made by Dr. Acheson's process, are examples of such lubricants, being diffusions of colloidal graphite in water and oil respectively.

I.—Characteristics of Solid Lubricants.

(a) *Graphite.*—Graphite is the most important of all solid lubricants. It is not altered in constitution by temperature and is remarkably resistant to the action of acids. It is not attacked by alkalis. It is, however, slowly attacked by powerful oxidizing agents, such as a mixture of potassium chlorate and concentrated nitric acid, which gradually converts it into a yellow substance containing both oxygen and hydrogen, termed Graphitic Acid or Graphitic Oxide. Some varieties are slowly attacked by boiling sulphuric acid and sodium nitrate.

Graphite is also called "Black Lead" or "Plumbago," but these names are slowly going out of use. Before the true chemical nature of graphite was established as being pure carbon, it was thought that it contained lead, and it was called "Black Lead" in consequence. Graphite is found in a natural form or may be produced artificially.

(b) *Natural Graphite.*—The greater part of the world's supplies of natural graphite come from Austria, Ceylon, Italy, Bavaria, Madagascar, the United States, Canada, Mexico, Japan, Siberia and England.

Natural graphite is found in two forms—Flake Graphite and Amorphous Graphite; the former is of a tough flaky structure and has a pronounced lustre, whereas the amorphous graphite has no such lustre.

Natural graphite, as it is obtained from the graphite mines, contains some impurities, chiefly silica, alumina and ferric oxides.

Three methods of purification are employed which may be classified as hand sorting, mechanical (dry or wet method) and chemical.

The specific gravity of natural graphite (2·2) and some of its impurities are so nearly identical that it is difficult to remove the impurities completely by mechanical means. For this reason, ingredients like mica and talc usually remain associated with purified natural graphite to a greater or less extent according to the process employed.

It is said that it is easier to purify the flake variety of natural graphite than the amorphous form; it is unquestionably a fact that most of the natural graphite employed for lubricating purposes is of the flake variety. The flake formation is retained even if it be ground into a fine powder. It is manufactured in several degrees of fineness, as for example, by the Joseph Dixon

Crucible Co., who obtain a high grade natural graphite from their Ticonderoga mines, which is practically free from impurities.

Several grades of flake graphite of British manufacture are marketed by the Graphite Products, Ltd., and have been analysed by L. Archbutt (*see* page 11).

Flake graphite may either be used dry, or in admixture with semi-solid lubricants. It cannot be used mixed with oil in ordinary lubricators or lubricating systems, because of its high specific gravity, which causes it to separate out and choke lubricators, oil pipes and oil grooves.

(c) *Artificial Graphite.*—Amorphous graphite is produced artificially by Dr. Acheson in the electrical furnace. He is able by his process to produce graphite of a soft unctuous non-coalescing nature and almost chemically pure.

The varieties produced for lubricating purposes are guaranteed to contain 99 per cent. of pure carbon, but usually contain more. In one variety of graphite, No. 1340, 98 per cent. of the graphite particles are less than $\frac{1}{338}$ in. in diameter.

From this or similar graphite Dr. Acheson produces what he calls deflocculated graphite by kneading it for a long time with water in the presence of a vegetable extract, such as tannic acid; the graphite particles in this process disintegrate into particles one thousand times less in diameter, in fact, Dr. Acheson estimates that each particle of the "1340" graphite becomes divided into 700,000 particles, a smallness of size bordering on the molecular, and the graphite becomes diffused in the water in colloidal form.

Dr. Acheson manufactures the colloidal solution of graphite in water in the form of a concentrated paste under the name of "Aquadag." It may be diluted by the addition of pure water to the required strength without separating out the graphite.

By a further process the concentrated Aquadag is mixed and kneaded with mineral lubricating oil until all the water is replaced by oil; this product is called "Oildag" and may be diluted with good quality neutral mineral oil without any appreciable separation of the graphite, without "flocculation," as Dr. Acheson calls it.

In Germany, colloidal solutions of graphite similar to Aquadag and Oildag, have been produced commercially by E. de Haen, the trade names being "Hydrosol" (corresponding to Aquadag) and "Oleosol" or "Kollag" (corresponding to Oildag). These German products are made from natural graphite by suitable corrosion, "stabilizing," etc., and from an examination by Professor D. Holde of Berlin, they appear to have the same stability (when diluted with water or oil respectively) as the colloidal artificial graphites made by Dr. Acheson's process. According to Professor Holde there are in both forms of colloidal graphites, graphite particles of a size from 1μ to 6μ but the majority are submicrons, less than 1μ in size (1μ = ·001 mm.) which are not easily separated out by centrifuging, whereas the larger particles from 1μ to 6μ are easily separated out in this manner.

Professor Holde found that by dissolving Oleosol in Benzol and filtering it through finely powdered bleaching earth, such as Fuller's earth, all the graphite was retained in the earth,

which owing to its absorbent properties acted as an ultrafilter, although the action was different from the mechanical pore-action of the usual ultrafilter.

Colloidal solid lubricants may be produced from materials other than graphite. It appears that some successful attempts have been made with Talc and Mica.

(d) *Talc.*—Talc consists of hydrogen magnesium silicate ($H_2Mg_3Si_4O_{12}$) and occurs as foliated or scaly compact masses. Its specific gravity ranges from 2·6 to 2·8.

The term *Steatite* is restricted to the compact massive varieties of talc.

Soapstone is an impure form of steatite.

French Chalk is talc or steatite in powder form.

Talc scales feel greasy or soapy, possess a perfect micaceous cleavage, have a pearly to silvery lustre and are flexible but not elastic, thus differing from mica.

Talc is very soft and can readily be scratched with the finger nail; it is selected as No. 1 in Mohs's hardness scale, although the harder varieties of talc may have a hardness of 2·5 to 4. The colour of talc varies from silvery white for the best and softest varieties to greyish or greenish for the harder steatite varieties.

Talc resists acids and alkalis and also cold and heat, no water being lost below a red heat.

Talc is obtained chiefly from the United States, but it is found also in many countries, England (Cornwall), Bavaria, France, Italy, Austria and India, being among the number.

(e) *Mica.*—The name "Mica" is applied to a group of minerals characterised by the facility with which they split into thin lamina which are flexible and more or less elastic. The hardness of the micas is between 2 and 3, whilst their specific gravity ranges from 2·7 to 3·1.

The chemical composition is subject to considerable variations in different species—broadly speaking, there is a group of potash micas, generally pale in colour and a group of magnesium or ferric magnesia micas, usually dark in colour.

All the micas are complex silicates containing aluminium and potassium generally associated with magnesium but rarely with calcium.

Water is always present and many micas contain flourine.

Mica is prepared for the market by splitting the blocks of rough mica into plates which are cut into the required patterns by means of shears.

The refuse mica when finely ground forms the material used for lubricating purposes. The small particles of mica still retain their thin lamellar structure.

(f) *Flowers of sulphur.*—Flowers of sulphur is not often used for lubricating purposes, but is used to some extent for curing hot bearings. It is a fine powder consisting of pure sulphur largely in the form of minute crystals. The specific gravity is approximately 2.

(g) *White lead.*—White lead is used to some small extent for curing hot bearings. It is an extremely fine powder consisting chemically of basic carbonate of lead generally said to have the following formula:—

$$2\,Pb.\,CO_3.\,Pb(OH)_2.$$

II.—The Action of Solid Lubricants.

It is generally agreed that the friction encountered in engines and machinery of all kinds is mainly dry friction or fluid friction, or a combination of both; the latter condition representing the state of affairs in the great majority of cases.

(a) *Dry Friction.*—All surfaces are more or less rough; even surfaces which are well machined and polished show under the microscope small projections and depressions.

It is an important fact that surfaces are rarely perfectly clean. Many chemically clean surfaces soon abrade and weld themselves together when rubbing over one another; fortunately, all surfaces are usually covered with what are termed contamination films of a more or less greasy nature; these films are due to the action or air, moisture, and impurities on the surfaces and they help to some extent in preventing abrasion, at any rate under low pressure conditions; in fact, they act very much like thin lubricating films.

The coefficient of friction corresponding to rubbing action between two unlubricated metallic surfaces normally ranges from 0·10 to 0·40 according to the hardness and smoothness of the surfaces and the rubbing speed: 0·16 may be taken as representing an average value for low speed conditions, but it is much greater in the case of soft solids such as lead.

Owing to irregularities of the rubbing surfaces, wear takes place, the softer surface being more rapidly abraded than the harder except when hard particles become embedded in the softer surface. The wear and friction is less for hard and smooth surfaces than for soft and rough surfaces.

Surfaces composed of the same material are more inclined to seize and weld than are dissimilar surfaces; for this reason materials of different hardness and composition are used for rubbing surfaces, as for example, a steel journal in a white-metalled bearing, soft cast-iron piston rings working against a harder cast-iron cylinder, &c.

Although the friction between solid surfaces is approximately independent of the area in contact, the wear increases as the contact area is diminished on account of the increased pressure per square inch.

On introducing a solid lubricant between otherwise unlubricated surfaces the finely divided particles of the lubricant associate themselves with one or other of the rubbing surfaces, filling in the pores and depressions and acting, to some extent, as a smoothing and polishing agent, covering the original surfaces with a thin smooth layer of the solid lubricant. As a result, the co-efficient of friction is reduced; the solid friction between the more or less rough original rubbing surfaces is replaced by the lesser solid friction between the smooth surfaces formed by the solid lubricant. When abrasion then takes place, it occurs not so much between the original surfaces (which possess great cohesion) as between the particles of the solid lubricant which have but little cohesion.

There are a variety of conditions for which dry solid lubricants have proved advantageous, as for example, in bearings or in such

parts of machinery as are apt to be neglected from a lubricating point of view, and which operate at low pressures and low speeds. When such surfaces are well coated with graphite, for example, and particularly if they are rubbed down to a dense glazed finish, the surfaces will work upon each other at low speeds for a long time with comparative freedom and without danger of cutting or wear taking place.

(b) *Viscous Friction.*—The object of lubrication by means of oil or semi-solid lubricants is that the lubricant shall attach itself to the rubbing surfaces and form a film between them, which under the prevailing conditions of speed, pressure and temperature will not be squeezed out but will keep the frictional surfaces apart.

This object is attained, in high speed bearings, as for example, stream-fed bearings lubricated by a circulation oiling system as in steam turbines and high speed steam engines, many ring oiling bearings, Michell bearings, the bearings of railway vehicles, &c.

In bearings thus perfectly lubricated the "rubbing" surfaces do not touch one another during running conditions and the friction is entirely dependent on the viscosity of the lubricant at the working temperature of the oil film.

The coefficient of friction corresponding to viscous friction is very low, ranging normally from 0·002 to 0·01 according to the viscosity of the lubricant and the weight on the bearing.

The application of solid lubricants to bearings lubricated in the manner described above would at first sight appear to be of no value; the journal floats on a film of oil and the presence of small particles of a solid lubricant does not increase the viscosity to an appreciable extent. The friction under running conditions is therefore not increased unless the solid lubricant is present in such an amount that the particles "crowd" the oil film especially at the "point of nearest approach" between journal and bearing and commences to act as an abrasive powder.

It has repeatedly been noticed in experimental work that immediately after a temporary application of solid lubricant in powder form the friction is much increased, but is reduced afterwards, when the particles have had time to attach themselves to the rubbing surfaces and form a smooth coating." The virtue in the employment of a solid lubricant lies entirely in the effect it produces on the rubbing surfaces themselves. With perfectly lubricated bearings the chief advantage of using a solid lubricant is apparently the effect on the friction at the moment of starting and at very low speeds, which results in a reduction in the static coefficient of friction, and prevents the surfaces from injuring each other until the lubricating film forms."

(c) *Static and Kinetic Friction.*—When surfaces have been at rest for some time the oil film is more or less completely squeezed out, and a certain amount of solid contact takes place.

As a result, the starting effort, when the surfaces are again brought into motion, is much greater than the running effort; in fact, the static coefficient of friction usually approximates to the values applying to dry friction.

The high values for the static coefficient of friction explain the great effort often required to start engines or machinery from rest, and form one of the chief reasons why ball and roller bearings are used, as with surfaces in rolling contact, there is practically no difference between the static and kinetic coefficient of friction.

Mineral oils are almost completely displaced by pressure, but experience proves that fixed oils, or mineral oils compounded with a percentage of fixed oil, maintain a better film between the surfaces and that, therefore, the static coefficient of friction with the latter oils is less. As a result, not only is the starting effort reduced, but also the wear, caused by metallic abrasion during the initial period of starting.

The effect of the use of a suitable solid lubricant or a solid colloidal lubricant is, as we have seen, to reduce the tendency to abrasion and to produce smoothness of the surfaces. As the solid lubricant cannot be displaced by pressure, the static coefficient of friction is reduced as compared with the result obtained when oil alone is used, assuming that the solid lubricant is of such a nature and used in such a manner that has actually increased the smoothness of the rubbing surfaces.

Makers of the flake variety of graphite claim that this type of graphite lends itself better to the production of very smooth and slippery surfaces than the amorphous varieties; in bearings with rough or very rough surfaces the flakes adhere to one another and easily build up a surface. When the bearing surfaces are reasonably well finished, this " building up " action of flake graphite does not appear to be of special value, in fact it may be detrimental where small clearances exist, particularly if fed in excess.

(d) *Greasy Friction*.—The term " greasy friction " is applied to friction between solid surfaces coated with a thin unctuous layer which is capable of persisting under conditions of high pressure.

Under conditions of low speed and high pressure it is extremely difficult to obtain perfect film formation. The great majority of bearings are not stream fed but are supplied only with a limited amount of oil per minute; in such cases the surfaces are in an imperfectly lubricated or semi-lubricated condition, for which the coefficient of friction will range from 0·01 to 0·10 according to whether the surfaces are very poorly lubricated (approaching the condition of unlubricated surfaces) or well lubricated (approaching the condition of perfectly lubricated surfaces).

Under these conditions there appears to be great possibilities for the use of solid lubricants.

A good solid lubricant must possess ability to adhere to metallic surfaces and it must be capable of producing a smooth surface. Graphite possesses both of these properties to a marked degree. When rubbed between metallic or non-metallic surfaces, graphite whether of the flake or amorphous variety produces a coating which is smooth and unctuous. Talc and Mica do not adhere to surfaces as well as graphite does, nor do they produce so smooth a surface.

III.—Analyses of Lubricating Graphites.

A high degree of purity of the solid lubricant is necessary in connection with lubrication of all high-class machinery, whereas for rough bearings, operating under extreme conditions and on the verge of seizure, a small amount of impurities may not be detrimental.

Mr. L. Archbutt has analysed various samples of "Foliac" Flake Graphites, Amorphous Graphite (Dr. Acheson's No. 1340) and Colloidal Graphites (Dr. Acheson's Aquadag and Oildag) as shown in Table No. 1. He makes the following remarks with regard to the colloidal graphites, indicating the presence of the vegetable deflocculating agent:—

> "I have found that it is impossible to wash out the whole of the oil in "Oildag" with ether and consequently the extracted graphite still contains some oil. I have had a similar experience in the analysis of "Aquadag." Although this was very largely diluted and slightly acidified with hydrochloric acid, the precipitated graphite, after filtering and thoroughly washing until perfectly free from chlorides and drying, lost 9 per cent. when heated in a closed crucible. On heating some of this graphite in a dry test tube, white fumes were given off with a smell of burning vegetable matter, and a brown oily distillate condensed on the tube."

Table No. 1.

Analyses of Lubricating Graphites—supplied by The Graphite Products, Limited, Battersea.

Description.	Foliac Flake Graphite No. 100.	Foliac Flake Graphite B. 1371.	Foliac Flake Graphite No. 2.	Foliac Flake Graphite No. 1.	Foliac Flake Graphite No. 101.
Moisture	1·26	·32	·20	·29	·05
Further loss on heating 5 minutes at faint redness in closely covered crucible... ...	·09	·49	·42	·44	·34
Mineral Matter (Ash).	·37	4·79	1·93	9·87	·05
Graphite (by diff.)	98·28	94·40	97·45	89·40	99·56
	100·00	100·00	100·00	100·00	100·00
Composition of Mineral Matter :—					
Silica		3·00	1·06	4·84	
Alumina ...	Mainly	·67	·33	3·32	
Ferric Oxide ...	Ferric	·86	·46	1·55	
Lime &c (by diff.)	Oxide	·26	·08	·16	
		4·79	1·93	9·87	

Analysis of Acheson Graphite, Grade No. 1340.

Moisture	·07
Further loss on heating 5 minutes at faint redness in closely covered crucible	·23
*Mineral Matter (Ash)	·66
Graphite (by difference)	99·04
	100·00

Composition of Mineral Matter:—

Silica	·07
Alumina	·31
Ferric oxide	·25
Lime, &c. (by difference)	·03
	·66

Analysis of "Aquadag."

The sample smelled distinctly of Ammonia and was found to contain:—

*Insoluble in water after coagulation by acidifying slightly	15·06
Water extract (by difference)	84·94
	100·00

**Analysis of this gave the following results:—*

Loss on heating 5 minutes at faint redness in closely covered crucible	9·12
Mineral matter (ash)	1·20
Graphite (by difference)	89·68
	100·00

Composition of Mineral Matter:—

Silica	·24
Alumina	·18
Ferric oxide	·65
Lime, &c. (by difference)	·13
	1·20

Analysis of "Oildag."

*Graphite, &c., insoluble in ether	11·2
Ether extract (oil)	88·8
	100·0

* It was found impossible to completely free the graphite from oil by washing with ether. Analysis of the "Graphite," as extracted, gave the following results:—

Loss on heating 5 minutes at faint redness in closely covered crucible	7·01
Mineral matter (ash)	2·25
Graphite (by difference)	90·74
	100·00

Composition of Mineral Matter:—

Silica	·21
Alumina	·35
Ferric oxide	1·02
Lime, &c. (by difference)	·67
	2·25

For convenience of comparison, the above analyses have all been recalculated on the moisture-free and volatile matter-free samples, and the results are given below:—

——	Acheson Graphite No. 1340.	"Aquadag."	"Oildag"	"Foliac" No. 100.	"Graphite" B. 1371.	"Foliac" No. 2.	"Foliac" No. 1.	"Foliac" No. 101.
% of graphite	99·34	98·68	97·58	99·62	95·17	98·06	90·06	99·95
% of Mineral Matter (Ash)	·66	1·32	2·42	·38	4·83	1·94	9·94	·05
	100·00	100·00	100·00	100·00	100·00	100·00	100·00	100·00

The "Foliac Special Large Flake Graphite No. 101" is almost chemically pure. The flakes have a pure silvery lustre when reflecting light, when not reflecting they appear absolutely black; a little of the Graphite lying at the bottom of a deep narrow trough of white paper looks black and white, as if it were a mixture of two substances.

The "Foliac" No. 100 is apparently the same Graphite as No. 101, ground very fine, and it contains more impurity, chiefly iron from the mill.

The "Acheson Graphite No. 1340," though of great purity, is less pure than the natural Graphite, and it is of interest to note that the conversion of this into "Aquadag" has introduced more impurity, and the further conversion of this into "Oildag" still more. In all the Acheson Graphites the principal impurities are iron and alumina. In the "Foliac" Graphites, silica is the chief impurity. Another point to note, which may be of considerable importance, is the tenacity with which the vegetable matter and oil used in preparing "Aquadag" and "Oildag" clings to the particles of graphite and cannot be removed by solvents.

IV.—The Grading of Graphite.

In the case of well finished rubbing surfaces very finely divided graphite must obviously be used, and the coating of the surfaces is easier to accomplish than with rough surfaces. Under these conditions, makers of amorphous graphite claim that flake graphite, when used in excess, is apt to build up too thick a surface, and reduce the working clearance to a dangerous extent, whereas with amorphous graphite, excessive use can have no ill

effects; the soft amorphous grains are easily crushed; in fact, a surface of fine amorphous graphite under pressure moves within itself like a film of oil.

With highly finished and polished surfaces operating with small clearances it would seem undesirable to use powdered lubricants, however finely they may be pulverised. Colloidal lubricants appear to be the only solid lubricants likely to give satisfaction under such conditions.

Mr. T. C. Thomsen has examined Dr. Acheson's Graphite No. 1340 and the various Foliac Flake Graphites for fineness, the grading being given in Table No. 2.

Foliac Flake Graphite No. 100 is exceedingly fine, although not so fine as Dr. Acheson's No. 1340.

TABLE No. 2.

Grading of Graphites.

Sieve No. of meshes per inch.	Acheson's Graphite No. 1340.	Foliac Flake Graphite No. 100.	Foliac Flake Graphite B. 1371.	Foliac Flake Graphite No. 2.	Foliac Flake Graphite No. 1.	Foliac Flake Graphite No. 101.
	%	%	%	%	%	%
10/10	—	--	—	—	2·0	10·0
20/20	—	—	—	—	15·0	40·0
30/30	—	—	—	—	20·0	24·0
40/40	—	—	—	1·0	22·0	20·0
50/50	—	1·0	·2	2·0	37·0	6·0
80/80	—	1·0	·2	2·0	2·0	—
100/100	2·0	4·0	36·4	56·0	1·0	—
200/200	98 0	94·0	63·2	39·0	1·0	—
FLOUR	95·5	89·6	Not tested.			

The figure given for each mesh sieve indicates the amount passing through that sieve and retained on the next sieve, for example :—

The percentage of "Flour" (impalpable powder) is an arbitrary figure, determined by Peterson's Florometer, which consists of a vertical torpedo shaped glass vessel 4′ 6″ high with a maximum diameter of 4″. The vessel is furnished with a 1″ opening at the top and is drawn out to a slender ½″ tube at the bottom. Five grams of graphite are placed in the vessel and an air current under 21 mm. pressure is passed in an upward direction through the vessel for 15 minutes. After the air current is switched off, the amount of graphite not blown away is weighed, the percentage of flour being thus easily determined.

Hardness of Solid Lubricants.

	Relative Hardness.
Pure Graphite	1·0
Best quality of Talc	1·0
Lower qualities of Talc or Soapstone ...	2·5 to 4·0
Micas	2·0 to 3·0

The admixture of a hard solid lubricant, like hard talc or mica, to a grease, particularly if an excessive amount is added, may cause a great deal of continuous but uniform wear, much more than would be caused by the grease used by itself, yet no cutting or excessive heating of the bearing may occur.

V.—Hot Bearings.

Hot bearings may be caused by excessive stresses, by the accidental entrance of gritty impurities, by a shortage of lubricant, &c., &c.

Whatever the cause may be the oil film becomes entirely displaced from a small portion of the bearing surface, a "dry" spot is formed, the surfaces enter into intimate metallic contact, the local temperature rises rapidly, the bearing seizes, and if it is lined with white metal, the latter may melt and flow out.

Under such conditions, when a bearing gives warning by heating, the usual procedure is to resort to the use of a fixed oil like castor or rape oil or to a viscous mineral oil like steam cylinder oil; the effect of using such oils is to produce a better film, which separates the metallic surfaces and reduces the temperature.

When the surfaces have commenced seriously to abrade one another, oils may prove of no avail, and solid lubricants must be used, such as graphite. The graphite particles by coating and impregnating the surfaces make it difficult for the metallic surfaces to seize, and if slight abrasion takes place in certain places, the graphite may often succeed in repairing the surface and make it possible for the normal lubricant again to take care of the condition.

Flowers of sulphur and white lead are often used to cure hot bearings; they act not so much as lubricants but rather as mild abrasives; they grind away the rough spots and produce a smooth surface.

Much more drastic remedies, such as salt, brick dust and grindstone dust have been successfully employed in very serious cases of large hot bearings; their function is quickly to grind away the rough parts which have commenced to seize. They may be applied mixed with thick steam cylinder oils or castor oil, in order to produce a thick film. The oil should be applied liberally in order to clean away the gritty powder after it has done its duty.

In bearings which are inclined to run hot, it is good practice occasionally to apply a small amount of graphite to produce a graphitised surface or to mix colloidal graphite with the normal lubricant, so as continuously to make up the wear on the graphite coating.

In overloaded worm gears, for example, which are continuously inclined to seize, it is good practice to mix a small amount of flowers of sulphur or fine graphite with the oil; they serve to prevent seizure and the wear becomes more uniform.

VI.—Methods of Applying Solid Lubricants.

Solid lubricants may be applied in three different ways:—

(*a*) Dry application.
(*b*) Mixed with semi-solid lubricants.
(*c*) Mixed with liquid lubricants.

(a) *Dry Application.*—Solid lubricants are applied dry in cases where for special reasons it is inadvisable or impossible to use an ordinary liquid or semi-solid lubricant.

The finely powdered solid lubricant is put into a linen bag and the bag is pounced or struck against the parts requiring lubrication, or a syringe like that used for applying insect powder may be employed to inject a cloud of lubricating powder into the bearings.

The following examples are illustrative:—

Lace-making Machines.—On certain reciprocating parts powdered graphite is used in place of oil, to avoid staining the fabric.

Bottle-making Machines.—Galvanizing Machines. Certain parts are exposed to extremely high temperatures; oil would burn away and leave a carbonaceous residue which would cause the parts to stick.

Chocolate Machinery.—To avoid dropping oil into the chocolate, all bearings may be lubricated entirely by dry graphite powder. The pressures and speeds are low, so that the friction developed is not too great for comfortable running.

Oilless bearings are made of a metal alloy, or of compressed wood, mixed with graphite, talc or other solid lubricant, or the graphite is firmly placed in the bearing in spiral grooves or strips, or again, the entire bearing may be made of compressed talc, soapstone or graphite.

Such bearings will often run without lubrication and without seizure, but the friction is very high as is also the bearing temperature.

For the lubrication of rubbing surfaces made of wood, graphite is very suitable; it is not absorbed, as is the case with oil. The graphite may also be applied mixed with grease, for the sake of convenience of handling.

Dry graphite in the form of small cylindrical sticks has been used in conjunction with oil for lubricating locomotive valves and cylinders, the oil being supplied by a separate lubricator. The graphite sticks are placed in a vertical tube and rest upon an abrasive wheel, which obtains a rotative or oscillating motion from some reciprocating part of the engine (the valve rod, for example). In this way, the wheel continuously abrades the graphite stick and the graphite powder drops down a vertical passage direct into the engine.

(b) *Mixture of Solid and Semi-solid Lubricants.*—The use of a solid lubricant in powder form is only resorted to in special circumstances. When there is no special objection to the use of a fluid or semi-solid lubricant and it is desired to use a solid lubricant, it is obviously desirable to mix the two together. Semi-solid lubricants are eminently suitable as carriers for solid lubricants because being non-fluid, they prevent separation of the graphite and, as they are themselves gradually consumed, they automatically supply the solid lubricant to the parts which they lubricate.

The admixture of solid lubricant usually ranges from 3 per cent. up to 10 per cent., rarely exceeding the latter amount. More graphite is required with grease than with oil because grease is usually employed for rougher conditions than oil, and more graphite is required to build up the surfaces and to maintain them in a smooth condition.

Speaking generally, semi-solid lubricants are always improved by the admixture of a small amount of finely pulverised pure flake or amorphous graphite. In this case, a softer grease, or a grease containing a lower viscosity oil can be employed, than that used without the addition of a solid lubricant. Exceptions are bearings with highly polished surfaces and small clearances and high class ball and roller bearings for which colloidal solid lubricants are the only solid lubricants that can be considered.

(c) *Mixture of Solid and Liquid Lubricants.*—Ordinary solid lubricants cannot normally be applied mixed with liquid lubricants, because, however finely the solids may be pulverised, their high specific gravity causes them to settle out in the lubricators, oil pipes, &c.

The finer the particles, and the more viscous the oil, the slower does separation take place, so that slight agitation may be sufficient to prevent separation. Mixtures of very finely pulverised solid lubricants and viscous oils, such as gear oil for automobile gear boxes may be kept mixed by the stirring motion set up by the gears.

Mechanically operated lubricators for steam engines are fitted with stirrers in the lubricator container as well as in the oil pipe leading from the lubricator to the engine to assist in preventing the graphite and oil from separating.

This problem of preventing separation of the solid lubricant is one that is causing many difficulties and cannot be said to have been satisfactorily solved, on account of the mechanical complications which are involved.

Chapman and Knowles have patented a mixture of finely pulverised graphite and glycerine for lubricating steam engine cylinders. Before mixing with the glycerine the graphite is impregnated with a sufficient amount of petroleum or other hydrocarbon insoluble in glycerine, to reduce the specific gravity of the mixture to that of glycerine. As a result, the "graphite-petroleum" specks will remain in suspension in the glycerine and the mixture can be pumped by a mechanical lubricator and supplied to the steam engine in the ordinary way.

Solid lubricants can, of course, be mixed with oil and, in the form of a more less liquid paste may be applied by hand to the bearings or parts requiring lubrication. This method is the one employed when "curing" hot bearings. Makers of flake graphite recommend the admixture of 3 to 4 per cent. of flake graphite with the oil; if too much graphite be used the friction is increased; if appreciably less than 3 per cent. be used the graphite coating on the bearing will not be fully maintained.

It would appear that the only really satisfactory way in which a solid lubricant can be automatically applied mixed with a liquid lubricant is to bring the solid lubricant into such a finely

divided state that the particles become of a size approximating that of submicrons. This state of fineness cannot be obtained by mechanical means alone, but has been attained by certain processes, such as Dr. Acheson's process already referred to. Colloidal solid lubricants, when diluted with pure oil (Oildag, Oleosol) or pure water (Aquadag, Hydrosol) do not separate out to any extent; they can be diluted to any extent and can therefore be applied to any engine or machine, mixed with the diluent which serves as a carrier.

Makers of colloidal graphite find that a very small percentage of graphite is ordinarily required in the diluted colloidal lubricant. Dr. Acheson recommends a graphite content of 0·35 per cent. for most purposes. That this small amount has been found sufficient is probably explained by the fact that colloidal lubricants are chiefly used on high-class machinery with reasonably well finished bearing surfaces.

*Mr. Archbutt has made some syphoning tests with Oildag and has proved that deflocculated graphite will pass over with lubricating oil through worsted trimmings with but little loss of its graphite content.

Many mechanical lubricators employ a sight feed arrangement, through which the drops of oil rise through a sight glass filled with water; no difficulty is experienced with oil containing colloidal graphite, as the surface of the oil is not penetrated by the water. It is different with watery solutions of colloidal graphite such as Aquadag; they obviously cannot be passed through water. Johnston has patented a lubricator with a sight feed glass filled with kerosene, through which the drops of diluted Aquadag sink down on account of their higher specific gravity as compared with kerosene. This arrangement has proved quite satisfactory for feeding Aquadag into the steam pipes of engines using saturated steam.

VII.—Drawbacks to the Use of Colloidal Solid Lubricants.

One unsatisfactory feature of colloidal graphite solutions is their black, "inky" nature, which creates strong prejudice against their use on the part of operators of engines or machinery; colloidal graphite stains are difficult to remove from the hands, &c. Colloidal talc will probably prove less objectionable in this respect than colloidal graphite.

The great drawback to all colloidal solid lubricants is, however, their susceptibility to the action of electrolytes, as for example, acids and alkalis. The presence of electrolytes effects rapid destruction of the colloidal films and flocculation or separation of the solid lubricant from the liquid in which it is diffused. The following experiments with dilute diffusions of oildag and aquadag in oil and water, respectively, containing various percentages of mineral acid, alkali, fatty acid, acetic acid and petroleum acid show the tendency to flocculation. The oil used for the oildag experiments was a neutral filtered spindle oil to

* Archbutt and Deeley: "Lubrication and Lubricants," p. 152.

which was added the amount of oildag recommended by the makers, giving a graphite content of 0·35 per cent. of the blended oil. The results are as follows:—

Mineral Acid.—It was found that even the slightest trace of sulphuric acid (H_2SO_4) precipitated the graphite. 0·1 per cent. of sulphuric acid caused flocculation inside 24 hours; 0·005 per cent. caused complete flocculation in three days.

Alkali.—The results with an alkali (caustic soda) were very similar.

Dr. Acheson himself has realised the importance of the purity of the mineral oils or water used for mixing with oildag or aquadag, respectively; he states:—

> "With deflocculated graphite the very best results will be obtained when the water or oil is absolutely pure, but commercially we may perhaps always have a very slight sedimentation of the graphite. The manufacture of practically pure or neutral petroleum oil may be made quite commercial, the presence of impurities in the oil now placed on the market being almost solely due to the failure of manufacturers properly to wash the oil. True, in some instances, while thorough washing may be performed with water, the water itself is not pure, which would still cause impurities to be found in the oil that would be capable of causing sedimentation of the graphite, but this residue, which is left by natural waters when they be of an impure nature, could finally be removed by a finishing wash with distilled water."

It is a fact that most if not all acid treated oils on the market are quite unsuitable for mixing with colloidal lubricants. The most suitable oils are perhaps the so-called neutral filtered oils, which during the process of refining have not been in contact with acids or alkalis, but are refined by earth filtration only. Most neutral filtered oils are only produced with low viscosity, and so the more viscous neutral lubricating oils suitable for blending with colloidal lubricants may have to be made by mixing a neutral filtered oil with so-called "filtered steam cylinder stocks" (which are undistilled residues from the distillation of a petroleum lubricating crude, which have subsequently been treated by earth filtration only).

Even with the best of neutral filtered oils, very slight sedimentation takes place, but it is so slight as not to be of practical importance. The purity required of the mineral oil is, however, so essential that users of colloidal lubricants should be warned not to mix them with the ordinary grades of oils, unless they have the assurance of their suppliers that none of the ingredients present contain acid or alkali or have been acid treated.

Fatty Acids.—The flocculating action of fatty acid is not so marked as with mineral acid. 0·3 per cent. of linseed oil fatty acid precipitated the graphite in four days; 0·1 per cent. of the same acid two weeks completely to precipitate the graphite. Professor Holde states that "free organic acid need not always act as a coagulant even with colloidal graphite; small quantities may under certain circumstances act as a stabiliser."

This experiment shows that, if precipitation of the graphite be avoided, colloidal lubricants should not be mixed with fatty oils or compounded oils which contain a fair amount of fatty oil.

Most oils used for marine steam engines, locomotives and other severe services are heavily compounded with vegetable or animal oil (from 10 per cent. to 30 per cent.) and contain an amount of free fatty acid, usually exceeding 0·5 per cent.

Acetic Acid.—The action of acetic acid was found to be similar in intensity to the action of mineral acid.

Petroleum Acids.—Petroleum acids (of a fairly volatile organic character) may be produced, during use, in oils employed in circulation systems in automobile engines, gas engines, oil engines and Diesel engines.

In the experiments under consideration, petroleum acid was produced in the oil by blowing air through neutral filtered spindle oil heated to a high temperature (360° F.–400° F.) to accelerate the oxidation and the formation of acid. To the oil thus prepared was added the prescribed amount of oildag. The presence of 0·1 per cent. of petroleum acid caused complete precipitation of the graphite in five hours.

On repeating the experiment with another sample of oil similarly treated, but only slightly "blown," containing 0·01 per cent. of petroleum acid, the flocculating action was much less marked, but after 2 weeks complete separation took place.

The amount of petroleum acid produced in the oil during prolonged use in an automobile engine will not be very great; 0·01 per cent. may be considered an average amount, assuming that the oil is a neutral filtered oil, and as oils for automobile use are fairly viscous, there is perhaps not much to fear from the presence of petroleum acid. Obviously, the more viscous the oil the slower the graphite separates out.

With splash oiling systems which do not depend on circulation of the oil by means of a pump, there is no danger in the use of colloidal lubricants, no matter what kind of oil is used, for if precipitation of graphite takes place, it will merely accumulate in the bottom of the engine and can do no harm. But with automobile engines employing an oil circulation system, highly purified neutral oils would appear essential in connection with colloidal lubricants, on account of the danger of choking up oil pipes, oil grooves, &c.

Oils taken from enclosed high speed gas and Diesel engines have been examined, which contained over 3 per cent. of free carbon in suspension, which had produced no ill effects on the engine. The carbon had been formed by carbonisation of the lubricating oil inside the cylinders, and had worked its way down into the crank chamber and mixed with the oil; probably a large amount of this carbon was present in colloidal form. It is a well-known fact that black waste oil from internal combustion engines of all kinds cannot be freed from its carbon content by filtration and that gravity separation in settling tanks may take months to accomplish and is rarely completely satisfactory.

The normal graphite content of 0·35 per cent. in an oil blended with colloidal graphite, if separated out in an engine, would be

considerably less than the 3 per cent. of free carbon referred to above, but its nature being different, only practical experience can determine the actual risk incurred, if any, by the use of such "impure" oils, as will cause precipitation of the graphite.

Emulsifying effect of water.—A quantity of diluted oildag was mixed with an equal amount of distilled water and shaken in a reciprocating bottle-shaking machine for 5 minutes at room temperature. All of the colloidal graphite emulsified with the water and formed a tenacious sludge which, on standing, separated out between the clear oil at the top and the clear water at the bottom.

It would appear, therefore, that colloidal lubricants should not be recommended for use in circulation oiling systems, when water is likely to enter the system, as is invariably the case with steam turbines, enclosed type steam engines, force-feed lubricated steam engines and the like.

In many enclosed type internal-combustion engines (automobile engines, gas engines, &c.) there is no great likelihood of water mixing with the oil in service, and no objection can be raised to the use of colloidal lubricants from this point of view.

When it is desired to apply colloidal lubricants temporarily to certain bearings, there is no objection to mixing them with the lubricant in use, independent of the character of the oil, because the mixture is immediately introduced, and there is no time for the colloid to separate out and cause trouble.

If mixtures of "impure" oil and colloidal lubricants are used continuously for a period by one of the many comparatively slow-feed oiling arrangements (bottle oiler, syphon oiler, drop-feed oiler, pad oiler, &c.) the colloid will flocculate and accumulate, the flow of oil not being sufficient to wash it away. As a result, narrow oil passages are choked, the supply of lubricant ceases, and trouble may easily occur.

VIII.—Observations on Results Obtained by the Use of Solid Lubricants.

(a) *Bearings.*—There are numerous experiences which testify to the value of solid lubricants and graphite in particular for use in bearings.

One British railway reports that good results have been obtained by using either colloidal graphite or flake graphite mixed with their ordinary loco engine oil. The graphite is not used for regular running (the compounded loco engine oil would cause flocculation of colloidal graphite, and flake graphite cannot be suspended in the oil), but only as a temporary remedy, whenever important bearings are inclined to heat.

Several works report that by continuous use of colloidal graphite mixed with pure mineral oils they have obtained excellent results on heavy duty bearings (heavy pumping engines, &c.) which previously gave trouble, even when using oils heavily compounded with fixed oil. Not only did the bearings run cooler, but also with an appreciable reduction in consumption of oil and without flocculation of the graphite.

Where no care has been taken to provide specially pure mineral oils, flocculation has occurred and choking of oil channels, &c., has resulted.

Some bearings of high-speed fans, which were troublesome with oil alone, ran reasonably cool when using the same oil mixed with colloidal graphite.

A maker of dictating machines found that customers did not trouble to oil the motors; they tried oildag and found that even when the motors received no oil for several months after the initial application of oildag, no scoring occurred, owing to the graphitised surfaces produced in the bearings.

One maker of jaw crushers lubricated the pitman bearing by a continuous flow of water mixed with some Hudson's soap extract and bicarbonate of soda. The pitman always groaned for about 15 to 20 minutes after starting up; since using Aquadag mixed with the water the groaning entirely ceased.

Saving in power has been reported by several firms resulting from the admixture of colloidal graphite with the oil in use.

One important maker of ball and roller bearings deprecates the use of graphite altogether for such bearings, reporting several decided failures as a result of using graphite.

As the chief object in providing lubrication for ball and roller bearings is to maintain the highly polished hard surfaces in good condition and little lubricating properties are required, it would appear inadvisable to use powdered or flaky solid lubricants for this purpose, as they would probably not improve the surface of the balls, rollers or races; only colloidal lubricants seem to have a chance of success for such bearings. The only ball and roller bearings in which the nature of the lubricant has an influence on the friction are those in which pure rolling does not take place, *i.e.*, in 3 or 4-point contact ball bearings and in roller bearings which develop end thrust; here some rubbing takes place under extreme pressures, and if the surfaces are impregnated with an exceedingly fine solid lubricant they are likely to operate with less wear and friction.

Some large lifts have vibrator wheels about 5 feet in diameter, which travel along a smooth shaft 8 inches to 9½ inches diameter. These wheels are bushed with cast-iron and require careful and reliable lubrication. It has been found that by replacing ordinary lubricating grease with a grease containing artificial amorphous graphite the number of scored shafts and the amount of wear were materially reduced.

(b) *Worm Gear.*—The lubrication of worm and worm-wheel reduction gears is always difficult; the pressure between the teeth is very great; even with an abundant supply of oil, the friction consists of a certain amount of dry friction in addition to fluid friction. It is therefore to be anticipated that the use of graphite in connection with the gear oil would prove beneficial, and the results of experiments carried out at the National Physical Laboratory with oildag and flake graphite on the Lanchester worm-gear testing machines show this to be the case.

These experiments show that in certain cases the addition of oildag to a mineral oil of relatively low lubricating value improves the gear efficiency, so that the results are equal to those obtained by superior mineral oils used in the same apparatus without admixture.

Fine flake graphite (Foliac No. 100) also improves the efficiency with most of the mineral oil tested, and where an improvement was recorded it was greater than with oildag. The results appear, however, to be less consistent, and there was evidence of greater wear than that taking place with oildag.

When the temperature of the oil is increased, a critical point is reached at which the gear efficiency rapidly decreases. The effect of adding oildag or flake graphite was in every case to raise the critical temperature about 18° C. so that an increased margin of safety in operation was thus obtained; this occurred even if the addition of solid lubricant did not increase the gear efficiency at lower temperatures.

(c) *Steam Cylinders and Valves.*—In many steam plants great economies could be effected if the exhaust steam could be utilised for heating or drying purposes, for washing or cooking, or if the condensed steam could be used as hot feed water. One reason why this is not done more often is the presence of cylinder oil in the exhaust steam. The oil can be entirely eliminated from the condensed steam by electrical or chemical means, but not from the exhaust steam itself before condensation, although good oil separators may take out as much as 99 per cent. if the cylinder oil is pure mineral in character, *i.e.*, not compounded with fatty oil, such as tallow oil.

An interesting paper was read by Mr. E. W. Johnston in 1916 before the Birmingham Association of Mechanical Engineers in which he gives his experiences on the lubrication of steam cylinders and valves by means of colloidal graphite (Aquadag diluted with water); the graphite content of the diluted mixture being 0·35 per cent.

When a suitable lubricator had been devised by Mr. Johnston, Aquadag was adopted as a cylinder lubricant in February, 1912, on a plant including three 50 kilowatt high speed vertical steam dynamos, two deep bore-hole pumping engines, boiler feed, circulating and other steam pumps supplied with saturated steam at 120-pound pressure.

The following results were quoted by Mr. Johnston in his paper:—

> "One of the high speed engines, after accurate gauging of the valves and cylinders, was put on a six months' running test. At the end of this period the greatest wear at any point was found not to exceed one-thousandth of an inch, and it was particularly noticed that the walls of the high pressure cylinder and piston rings were in faultless condition, having mirror-like surfaces. Since uniformly satisfactory results were obtained also on the pumping engines and other auxiliaries, the entire plant has been working with

aquadag as the sole cylinder lubricant from February, 1912, up to the present moment. All available condensed steam is now returned to the boilers, so that approximately 10 per cent. only of make-up water is added daily. The interiors of the boilers are free from grease, practically clean down to metal, save where patches of old scale still adhere, and entirely free from suspicion of "pitting." Formerly a considerable amount of scale of very tenacious character had to be dealt with, which resulted in loss of efficiency, extra labour and wear and tear to the boiler. Now, on the other hand, a feed water of considerably higher temperature and exceptional purity is available, resulting in further considerable fuel economy. After almost five years' daily use, there is found to be no deposit throughout the receivers, ports, valves and cylinders in excess of the thin coating formed in the first few weeks of use, and little if any trace in the exhaust pipes, condensers or other tracts beyond the engines."

Photomicrographs of a portion of the piston rings show that the minute depressions or pores in the cast-iron have been filled up with graphite and that the graphite coating is essentially a surface coating, although slight penetration of graphite was observed in a small soft area of the surface.

It is reasonable to assume that Aquadag can be used on larger vertical engines than those referred to by Mr. Johnston, as it is fairly easy to lubricate vertical steam engines. The lubrication of horizontal engines is more difficult, and no experiments appear to have been made with Aquadag on such engines.

It would be interesting to know how far Aquadag or some other aqueous colloidal lubricant can be used in connection with steam motor vehicles and the like where it is desired to use condensers for the exhaust steam; its use would make oil separators unnecessary and reduce scale formation in the boilers.

The use of aqueous colloidal lubricants is probably limited to engines employing saturated steam and engines of small power; it must be kept in mind that if it were not for the water film produced by steam condensation in the cylinder, the friction would be very high indeed. In engines employing superheated steam, there is little or no condensation in the cylinders and it becomes necessary to provide a lubricating film in order to avoid excessive friction and wear.

Many experiments have been made with graphite and oil for the internal lubrication of steam engines employing superheated steam; pure fine flake graphite may be used, or colloidal graphite may be mixed with the cylinder oil, which should preferably be a pure mineral oil, not compounded with fatty oil, as is the case with most good quality steam cylinder oils.

The results of graphite employed in this way have in many cases been satisfactory; appreciable reductions in consumption of oil have been recorded, also less wear of internal moving parts. Alongside these results there are also a great many failures, although no failures have been reported with colloidal

graphite. The failures with flake graphite have been due to excessive and injudicious use of the graphite, or to the use of coarse or impure graphite, or to breakdown of the complicated lubricators required to keep the graphite-oil mixture well stirred.

Under superheat conditions the surfaces are more difficult to lubricate than with saturated steam and the necessity for not overfeeding with graphite will be readily understood. Excess graphite accumulates behind the piston rings and in the metallic packing, and will in time make the rings inflexible in their grooves, resulting in scoring of the surfaces, leakage of steam past pistons and piston rods, &c.

Great care must be exercised in the use of flake graphite for superheated steam conditions, and only the purest graphite must be used, in order to avoid excessive wear of pistons, piston rings, cylinders, piston rods, metallic packings, &c.

Graphite has been used by many marine engineers for lubricating large unbalanced "D" type slide valves. Cast iron being more or less porous is a material particularly likely to benefit from the use of graphite: when the pores are filled and a graphite coating is produced it will be found that an exceedingly small amount of graphite is required to maintain the surfaces in good condition. Impregnation of such surfaces with graphite reduces the tendency to abrasion and makes it easier for the cylinder oil to maintain efficient lubrication.

When a mixture of flake graphite and cylinder oil is used for the internal lubrication of steam engines, the graphite will in time find its way out with the exhaust steam; it is easily separated from the steam and deposited in the oil separator or hot well. Flake graphite will adhere to the baffles in the separator and accumulations should be removed at suitable intervals.

In all cases where the use of graphite has brought about a reduction in consumption of steam cylinder oil, it has also reduced the quantity of oil reaching the boilers, and therefore reduced the possibility of boiler troubles from this source.

(d) *Internal Combustion Engines.*—The use of solid lubricants for the internal lubrication of internal combustion engines has been the subject of much controversy and various opinions have been expressed regarding such features as preignition, carbon formation, sooting of sparking plugs, ease of starting, oil consumption and reduction in friction.

Contradictory reports have been received with reference to carbon formation and sooting of plugs. In small engines, such as motor cycles, no difficulty is experienced; some reports mention less sooting of plugs when using colloidal graphite, but this may perhaps be explained by a more economical use of oil when used with an admixture of graphite.

In the experiments carried out by the Technical Department of the Air Ministry on a Daimler engine and on aircraft engines lubricating with oildag and oil, marked sooting of the sparking plugs occurred.

The colloidal graphite is not consumed in the combustion space, but in the form of an exceedingly fine dust spreads and adheres to the walls of the combustion chamber and the sparking plugs. The greater the consumption of oil, and it is very great on aircraft engines, the larger is the amount of graphite deposited. It would appear desirable either to use a much smaller graphite content than 0·35 per cent. in the oil, or to design the engine and lubricating system in such a way that the oil consumption is appreciably reduced.

The formation of oil-carbon depends on the amount of oil burnt inside the cylinders and on the nature of the oil; some oils produce more carbon than others, but the amount of oil-carbon produced will normally never exceed 0·02 per cent. of the oil used. Although hydrocarbon oils contain over 80 per cent. of carbon, most of the oil is vapourised and decomposed into other hydrocarbons, with the result that the actual amount of oil-carbon formed is a very small percentage of the amount of oil consumed.

When mixing colloidal graphite with oil to give a graphite content of say 0·35 per cent. in the mixture, it must be remembered that this graphite is not consumed, and unless a very large reduction in oil consumption takes place, the formation of carbon will be greater than without the graphite.

Opinions appear to be unanimous that when using graphite, engines (motor cycles, automobile engines, gas engines, &c.) start more easily and with greater freedom.

Saving in oil consumption, made possible by the use of graphite, is due to the smoother surfaces of pistons and cylinders and the more uniform and slightly smaller clearance space between them; better compressions are also obtained due to less leakage past the piston. When the initial oil consumption is large, as with aircraft engines, the saving is apt to be overlooked, but with small engines and where adjustable mechanical lubricators are employed, the saving obtained may be quite considerable.

Speaking generally, half the friction in an internal combustion engine is piston friction; the lubricating oil film is probably never complete and a certain amount of metallic contact (dry friction) takes place.

In the United States colloidal graphite appears to be extensively used for the initial " running in " of automobile engines; it is said to save considerable time in producing a good surface and gives the engine a good internal " skin " before leaving the builders' works.

(e) *Ropes, Chains and Gears.*—Various greases are employed for the lubrication and preservation of ropes, chains and gears, and, as already mentioned, the admixture of a small amount of good quality finely divided graphite is beneficial. Messrs. Hans Renold, Ltd., find that with intermittently lubricated chain drives, graphite grease containing artificial amorphous graphite is very suitable. When the chain has been soaked in the hot

liquid grease it will work without further lubrication for a long period, sometimes for several months, whereas with thin oil in use it must be applied at least once a week, and then the results are not always satisfactory, a reddish deposit (rust) being found in the bearings of the chain. With graphite grease this deposit does not form.

The same firm also reports that the clutch band in their power clutches, when lubricated by graphite grease, requires no attention for long periods.

When chains or gears are enclosed in an oil-tight casing, the use of an oil bath is preferable to grease; in this case the admixture of a small amount of finely pulverised graphite or colloidal graphite is also beneficial. Messrs. Hans Renold, Ltd., report some interesting results from the use of diluted oildag in connection with chains, lubricated by an oil bath. Their figures are as follows:—

Power of motor	20 H.P.
Length of line-shaft	90 ft.
No. of line-shaft hangers	10
No. of chain drives	25
Total length of chain drives ...	275 ft.
Line-shaft speed	310 r.p.m.

Conditions.	Energy Consumption in Watts.			
	Starting up cold.	After short run.	After 105 hours run.	
			Starting up cold.	After short run.
Line-shaft hangers and chains lubricated with ordinary oil.	5000	4000	—	—
Chain lubricated with Oildag.	—	3750	—	—
Line-shaft hangers lubricated with Oildag.	—	3500	—	—
Chain and hangers lubricated with Oildag.	—	—	4000	3000
On further application of Oildag to chains.	—	—	—	2500

A further advantage we found from the use of Oildag was that the noise given off by the chains was considerably reduced.

(f) *Metal Cutting and Wire Drawing.*—Colloidal solid lubricants—such as aquadag—have been used as coolants for cutting purposes; experiments seem to indicate that colloidal solid lubricants are not satisfactory when used for this purpose by themselves. They do not flow to the tool point if it is greasy, and the

tool point therefore wears; when mixed with ordinary cutting emulsions or soap and water, good results have been obtained, but the high first cost of colloidal lubricants militates against their use for cutting purposes; the staining effect of the graphite on the hands of the operators is also objectionable.

In metal wire-drawing operations semi-solid lubricants are used, such as mixtures of olive soap and powdered talc. There appears to be no reason why a vegetable soap mixed with a suitable amount of finely powdered graphite should not be capable of rendering good service.

Aquadag is used in wire-drawing the metal filaments (Dempsters Patent No. 17,722 of 1911) used in electric lamps; the dies require a certain amount of lubrication to produce a satisfactory thread and aquadag is apparently the only non-oily lubricant which has given satisfaction for this purpose.

(*Continued from p.* ii *of cover.*)

Food Investigation Board. (*Special Report No.* 1.) Report of the Engineering Committee on the Design of Railway Wagons for the Carriage of Perishable Foods. 1919.
Price 3*d.* (by post, 4½*d.*).

*Second Report on Colloid Chemistry and its General and Industrial Applications. 1919.
Price 1*s.* 6*d.* (by post, 1*s.* 8½*d.*).

Fuel Research Board. Report on Pulverised Coal Systems in America, by L. C. Harvey. 1919.
Price 2*s.* 6*d.* (by post, 2*s.* 10*d.*).

Food Investigation Board. Report for the year 1918.
Price 3*d.* (by post, 4*d.*).

Food Investigation Board. (*Special Report No.* 2.) The Literature of Refrigeration. 1919.
Price 4*d.* (by post, 4½*d.*).

Fuel Research Board. Report to the Board of Trade on Gas Standards. 1919. (Cmd. 108.)
Price 1*d.* (by post, 2*d.*).

Report of the Committee of the Privy Council for Scientific and Industrial Research for the year 1918–19. (Cmd. 320.)
Price 6*d.* (by post, 7½*d.*).

LIST OF DOCUMENTS ISSUED BY THE DEPARTMENT.

Copies of the documents named below can be obtained free of charge on application to the Secretary, Department of Scientific and Industrial Research, 15, Great George Street, Westminster, S.W.1.

Pamphlets on the formation of Research Associations.

Research Association 1. (*Revised.*)	The Government Scheme for Industrial Research.
Research Association 2. (*Revised.*)	Draft Memorandum and Articles of Association for Research Associations.
Research Association 3. (*Revised.*)	Conditions as to the payment to Research Associations by the Committee of Council.
Research Association 4.	The method of subscription to Research Associations.

Bulletins.

No. 1. Memorandum on the Preservation of Timber in Coal Mines, 1917.

No. 2. Memorandum on Cutting Lubricants and Cooling Liquids, and on Skin Diseases produced by Lubricants, 1918.

No. 3. A Study on the performance of "Night Glasses," by L. C. Martin, B.Sc., &c. (*Lecturer in the Technical Optics Department, Imperial College of Science and Technology*). 1919.

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* The first Report was published by the British Association for the Advancement of Science, Burlington House, W.1.

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